DYNAMIC RESPONSE OF PILE FOUNDATIONS UNDER COUPLED VIBRATION

Final Year Project submitted to
National Institute of Technology, Rourkela
for the award of the degree
of
Bachelor of Technology

by

S. Santosh Kumar Prusty
Roll No: 10601021

under the guidance of
Dr. Bappaditya Manna

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

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ROURKELA

CERTIFICATE

This is to certify that the project entitled " dynamic response of pile foundation under coupled vibration " submitted by S.Santosh kumar prusty [Roll no. 10601021] in partialfulfilment of the requirements for the award of Bachelor of Technology degree in Civil engineering at the National Institute of Technology Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge the matter embodied in the project has not been submitted to any other university/institute for the award of any degree or diploma.

Date: 06.05.2010

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Date: 06.05.2010 **S.Santosh Kumar Prusry**

ABSTRACT

For the dynamic response of pile foundation under coupled vibration single piles and 2 x 2 group piles with length to diameter ratios 10,15 and 20 have taken. For group piles, spacing to diameter ratios of 2, 3 and 4 for each length to diameter ratio were used. Formulation of the theory of plane strain model of Novak (Novak, 1974) for horizontal and rocking vibrations to predict the dynamic response of single pile and pile group. Static interaction factors (El-Sharnouby and Novak, 1986) were determined to account pile-soil-pile interaction. By using Novak's plane strain model with static interaction factor approach the frequency independent dynamic response of both single pile and group of pile for horizontal vibration and rocking were determined. Finally the predicted response of single and group piles were compared with the observed response reported in Manna (2009)

List of Tables

List of Response curves

TABLE OF CONTENTS

Introduction

Pile foundations are widely used in weak soil deposits for supporting various structures. In addition to static loads, pile-supported foundations and structures are subjected to dynamic loads such as machine-induced vibrations, moving traffic, ocean waves and earthquakes. In recent years, with the development in the offshore structures technology and the nuclear power industry and other applications, the dynamic behavior of pile foundation has received a renewed attention.

The nature of the loading and soil-pile responses are quite different for different sources of dynamic loading. In machine foundations, the piles may be subjected to vertical oscillation, horizontal translation, rocking and torsion. Machines may cause only small amplitudes of vibrations, and soils may behave as elastic materials. The response of pile foundations under these dynamic loads is relatively more complex than for static loads. In the dynamic analysis of soil-pile-foundation, the interactions between piles and the surrounding soil represent one of the important topics of foundation dynamics. However this is least understood and is in urgent need for solution. Though a large number of analytical investigations on the dynamic response of pile foundation have been carried out over the last three decades, much has yet to be known about the effect of soil pile characteristics through systematic studies. At the same time, experimental investigation in the field on single pile and pile groups of different configuration in layered soils is also needed to validate the theoretical findings. However a very little information is available on observed dynamic behavior of pile foundations. This is mainly because of difficulties in conducting tests including a large number of variables both in soils and piles.

In present study, analytical investigation is carried out using plane strain model of Novak to validate the dynamic test results of piles (Manna, 2009) under coupled vibration. The dynamic tests were carried out on model reinforced concrete single pile (L/d = 10, 15, 20, where L is length of pile and d is diameter of pile) and 2 × 2 pile groups of different length and spacing (L/d = 10, 15, 20 and s/d = 2, 3, 4 where s is pile spacing). Frequency versus amplitude curves of piles were experimentally established in the field for different intensities of excitation, different static loads on pile, and different contact conditions of the pile cap with the soil. Important parameters that influence the dynamic soil-pile interaction for both single pile and pile group are studied for the investigation.

Review of Literature

Many analytical and semi analytical methods have been developed over the time to study the dynamic response of piles. Some of the methods are as follows:

(i) Equivalent cantilever method [Hayashi et al. (1965), Prakash and Sharma (1969)]

(ii) Lumped-mass-spring-dashpot model [Barkan (1962), Maxwell et al. (1969)]

(iii) Winkler foundation model [Matlock et al. (1978), Nogami et al. (1992)]

(iv) Novak's plane strain model [Novak (1974)]

(v) Finite element analyses [Bentley and El Naggar (2000)]

(vi) Boundary element method [Kaynia and Kausel (1982)]

(vii) Cone model [Wolf et al. (1992), Jaya and Prasad (2004)]

Though the response of pile foundations subjected to dynamic loading has been studied by several methods, Novak's Continuum approach or Novak's plane strain model (Novak, 1974) is widely used in practice. This pioneering works included the radiation damping in the analysis and offered a good insight into the behavior of piles under dynamic loads. Many researchers [Novak and Nogami (1977), Novak and El Sharnouby (1983)] used the Novak's plane strain model to determine the impedance functions for both vertical and horizontal vibrations. Novak and Aboul-Ella (1978) investigated the impedance functions of piles in layered media.

With the emergence of the new rather abstract theories for dynamic pile analysis, it became necessary to verify their validity by means of experiments. The full scale forced vibration tests in the field were conducted for both vertical and horizontal vibrations by many investigators [Jennings et al. (1984), Blaney et al. (1987), Han and Vaziri (1992)]. Field experiments with small prototype single piles and group of piles were conducted by

Novak and Grigg (1976) and Han and Novak (1988) subjected to strong horizontal and vertical excitations. A series of dynamic tests were conducted with a group of 102 closely spaced piles for vertical, horizontal and torsional mode of vibrations by El Sharnouby and Novak (1984). These experimental results were evaluated by Novak and El Sharnouby (1984) to determine if the theories available could predict the behavior of the test pile group. Krishnamurthy et al. (1982) and Ghumman (1985) conducted dynamic tests on different model piles and pile groups in the laboratory to study the dynamic behavior of pile foundation.

Objective and Scope of the Present Study

An attempt is made to study the dynamic response of single pile and pile group of different configurations in layered soil subjected to coupled vibration by analytical study. The detailed objectives of the present study are as follows:

1. Formulation of the theory of plane strain model of Novak (Novak, 1974) for horizontal and rocking vibrations to predict the dynamic response of single pile and pile group.

2. Determine the static interaction factors (El-Sharnouby and Novak, 1986) to account pile-soil-pile interaction.

3. Determination of the frequency independent dynamic response of both single pile and group of pile for horizontal vibration and rocking by Novak’s plane strain model with static interaction factor approach.

4. Comparison of the predicted response of single and group piles with the observed response reported in Manna (2009).

Experimental Study

The site was located adjacent to the Hangar, Indian Institute of Technology, Kharagpur Campus, India (Manna, 2009). Both disturbed and undisturbed soil samples were collected from three bore holes (BH) located at different places of the site. The subsurface investigation indicated that the test site consists of three different soil layers upto a depth of 2.80 m. The soil properties were determined by in-situ and laboratory tests. The laboratory experiments include natural moisture content (IS 2720 Part 2, 1973), specific gravity (IS 2720 Part 3/Sec 1, 1980; IS 2720 Part 3/Sec 2, 1980) Atterberg's limits test (IS 2720 Part 5, 1985; IS 2720 Part 6, 1972), particle size distribution analysis of soil (IS 2720 Part 4, 1985) and triaxial test (IS 2720 Part 11, 1993). Two in-situ tests, namely, crosshole seismic tests for determining the shear wave velocity (V_s) of soil layer and standard penetration tests (SPT) to determine N value were conducted. Crosshole seismic tests (ASTM D 4428/D 4428M, 2000) were conducted in the field.

Based on different field and laboratory observations the soil stratum was divided into three different categories as per Unified Soil Classification System (USCS). The soil profile consists of 1.20 m of soft yellow organic silty clay with low plasticity (OL) overlying 1.10 m thick layer of brown medium stiff inorganic clay with low to medium compressibility (CL). The third soil layer of red stiff inorganic clay with high compressibility (CH) mixed with gravel was found at the depth of 2.30 m and it extends upto the depth of 2.80 m.

The pile used in the study was a cast-in-place reinforced concrete circular pile. The diameter (d) of all the piles was 0.10 m. In total twelve sets of pile were used in this investigation. Three sets of single pile of three different lengths (L = 1.0 m, 1.5 m and 2.0 m) and nine sets of 2 × 2 group pile (Spacing s = 2d, 3d and 4d for each pile length L, where L = 1.0 m, 1.5 m and 2.0 m) were used for the investigation. The dimension of pile cap was 0.57 m × 0.57 m × 0.25 m.

Forced vibration tests were conducted on all single and group piles subjected to coupled vibration. The details of the testing procedure and test results are presented in Manna (2009).

Theoretical Study

The approximate analytical technique developed by Novak (1974) derives stiffness and damping constants for piles and pile groups, with the help of which lateral response is determined.

Lateral and damping constants for single piles with soil modulus constant with depth was derived by Novak (1974). Novak (1974) considered (1) horizontal alone, (2) rocking alone, and (3) coupled rocking and horizontal. Novak and El-Sharnouby (1983) extended these solutions to include parabolic variation of soil-shear modulus.

Horizontal

1. Stiffness and damping of single pile

$$k_x^1 = \frac{E_p I_p}{r_0^3}(f_{x1}) \quad (1)$$

$$c_x^1 = \frac{E_p I_p}{r_0^2 V_s}(f_{x2}) \quad (2)$$

2. Stiffness and damping of the pile group (of piles only)

$$k_x^g = \frac{\sum_1^n k_x^1}{\sum_1^n \alpha_L} \quad (3)$$

$$c_x^g = \frac{\sum_1^n c_x^1}{\sum_1^n \alpha_L} \quad (4)$$

3. Stiffness and damping due to pile cap

$$k_x^f = G_s h S_{x1} \quad (5)$$

$$c_x^f = h r_o(\sqrt{G_s \gamma_s / g}) S_{x2} \quad (6)$$

where values of S_{x1} *and* S_{x2} are horizontal stiffness and damping parameter for side

4. Total stiffness and total damping are then sum of stiffness and damping values computed in steps 2 and 3, respectively.

Rocking

1. Stiffness and damping of a single pile in both rocking as well as for coupled motion

$$k_\phi^1 = \frac{E_p I_p}{r_o}(f_{\phi 1}) \quad (7)$$

$$c_\phi^1 = \frac{E_p I_p}{V_s}(f_{\phi 1}) \quad (8)$$

$$k_{x\phi}^{1} = \frac{E_p I_p}{r_0^2}\left(f_{x\phi 1}\right) \tag{9}$$

$$c_{x\phi}^{1} = \frac{E_p I_p}{r_0 V_s}\left(f_{x\phi 2}\right) \tag{10}$$

2. Stiffness and damping of pile group (piles only) (Novak, 1974)

$$k_{\Phi}{}^{g} = \sum_1^n [k_{\Phi}^1 + k_w^1 x_r^2 + k_x^1 Z_c^2 - 2Z_c k_{x\Phi}^1] \tag{11}$$

$$c_{\Phi}{}^{g} = \sum_1^n [c_{\Phi}^1 + c_w^1 x_r^2 + c_x^1 Z_c^2 - 2Z_c c_{x\Phi}^1] \tag{12}$$

x_r = horizontal distance of pile from C.G. pacing of piles

Z_c = height of the centre f gravity of the pile cap above its base and

$\delta = h/r_o$

3. Stiffness and damping of pile cap

$$k_{\emptyset}^{f} = G_s r_0^2 h S_{\emptyset 1} + G_s r_0^2 h[\left(\frac{\delta^2}{3}\right) + \left(\frac{Z_c}{r_0}\right)^2 - \delta\left(\frac{Z_c}{r_0}\right)] S_{x1} \tag{13}$$

$$c_{\emptyset}^{f} = \delta r_0^4 \sqrt{G_s \gamma_{\frac{s}{g}}}[S_{\emptyset 2} + \left\{\frac{\delta^2}{3} + \left(\frac{Z_c}{r_0}\right)^2 - \delta\left(\frac{Z_c}{r_0}\right)\right\} S_{x2}] \tag{14}$$

4. total stiffness and damping are then the sum of stiffness and damping values computed in steps 2 and 3, respectively.

Coupled Response of Pile Foundation

The resonant frequency and amplitude of vibration of the foundation in coupled horizontal and rocking motion can be obtained by Beredugo and Novak (1972). With the total stiffnesses in coupled mode of pile foundation, the two resonant frequencies ω_{n1} and ω_{n2} can be obtained from the equation as given by

$$\omega_{n1,2}^2 = \frac{1}{2}\left(\frac{K_{uu}}{m_s} + \frac{K_{\psi\psi}}{I_\psi}\right) \mathrm{m} \sqrt{\frac{1}{4}\left(\frac{K_{uu}}{m_s} - \frac{K_{\psi\psi}}{I_\psi}\right)^2 + \frac{K_{u\psi}^2}{m_s I_\psi}} \tag{15}$$

The real amplitudes of vibration of coupled vibration are

$$u = P\sqrt{\frac{\alpha_1^2 + \alpha_2^2}{\varepsilon_1^2 + \varepsilon_2^2}} \tag{16}$$

$$\psi = M\sqrt{\frac{\beta_1^2 + \beta_2^2}{\varepsilon_1^2 + \varepsilon_2^2}} \tag{17}$$

where

$$\alpha_1 = K_{\psi\psi} - I_\psi \omega^2 - \frac{M}{P} K_{u\psi} \tag{18}$$

$$\alpha_2 = \left(C_{\psi\psi} - \frac{M}{P} C_{u\psi} \right) \omega \tag{19}$$

$$\beta_1 = K_{uu} - m_s \omega^2 - \frac{P}{M} K_{u\psi} \tag{20}$$

$$\beta_2 = \left(C_{uu} - \frac{P}{M} C_{u\psi} \right) \omega \tag{21}$$

$$\varepsilon_1 = m_s I_\psi \omega^4 - \; m_s K_{\psi\psi} + I_\psi K_{uu} + C_{uu} C_{\psi\psi} - C_{u\psi}^2 \;\; \omega^2 + \; K_{uu} K_{\psi\psi} - K_{u\psi}^2 \tag{22}$$

$$\varepsilon_2 = - \; m_s C_{\psi\psi} + I_\psi C_{uu} \;\; \omega^3 + \; C_{uu} K_{\psi\psi} + C_{\psi\psi} K_{uu} - 2 C_{u\psi} K_{u\psi} \;\; \omega \tag{23}$$

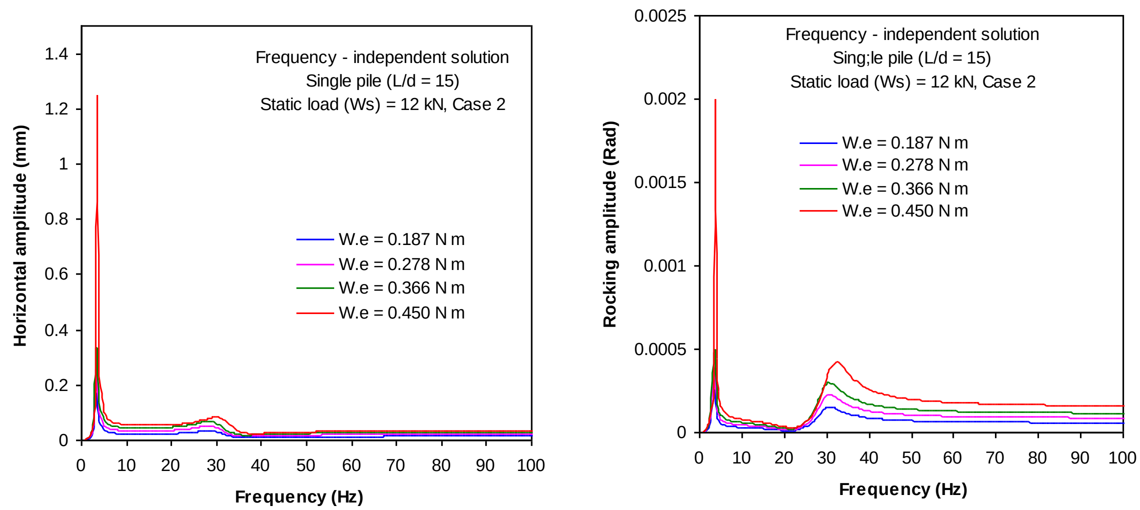
where P = real amplitude of horizontal force, M = real amplitude of moment, K_{uu}, $K_{\psi\psi}$, $K_{u\psi}$ = total horizontal, rocking and cross stiffness constants of pile foundation, C_{uu}, $C_{\psi\psi}$, $C_{u\psi}$ = total horizontal, rocking and cross damping constants of pile foundation.

Theoretical Response Curves

A set of response curves were plotted for different excitation levels using plane strain approach of Novak (1974). Typical horizontal and rocking response curves of a single pile (L/d = 15, W_s = 12 kN) obtained from coupled vibration test - Type 1 with different excitation intensities are presented in Figs. 1(a) and (b) respectively for no contact condition of pile cap. The frequency versus amplitude response curves of pile group (L/d = 15, s/d = 4, W_s = 12 kN, Case 2) for both horizontal and rocking motion are presented in Figs. 2(a) and (b).

Important observations made from Figs. 1 and 2 are summarized below:

1. Two resonant peaks are observed at two different frequencies for both horizontal and rocking component.
2. The second resonant peak is well separated from the first peak.
3. The first resonant peak of the coupled response is dominated by the both horizontal translation and rocking.
4. As the excitation moment increases the resonant amplitude increases but the resonant frequency remains same.



(a) (b)

Fig. 1. Frequency versus Amplitude Curves Obtained by Linear Analysis of Coupled Vibration for Single Pile (L/d = 15, W_s = 12 kN, Case 2), (a) Horizontal Component, (b) Rocking Component

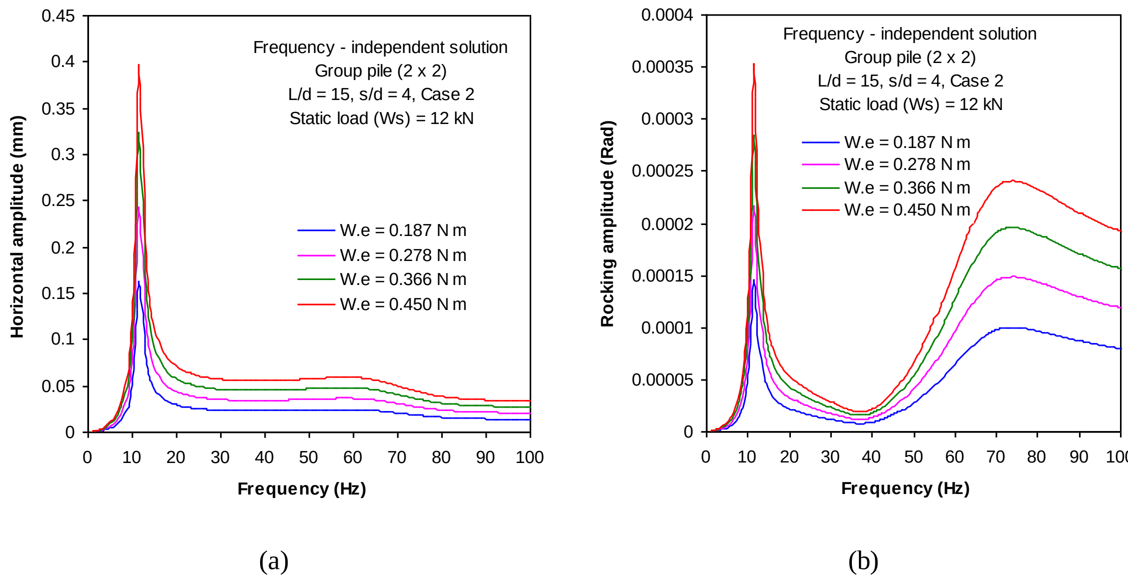


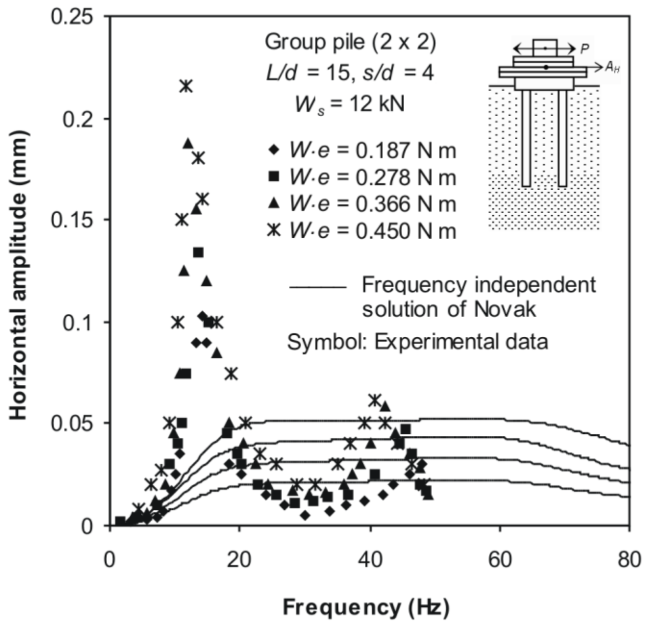
Fig. 2. Frequency versus Amplitude Curves Obtained by Linear Analysis of Coupled Vibration for Group Pile (L/d = 15, s/d = 4, W_s = 12 kN, Case 2), (a) Horizontal Component, (b) Rocking Component

To study the effect of various influencing parameter, namely, spacing of pile in a group, length of pile, embedded conditions of pile cap, analytical results are presented separately for coupled vibration. It was observed that the resonant frequency increases with increasing pile spacing for both first and second vibration mode. However, the resonant amplitudes increases for first mode and decreases for second mode of vibration for increasing pile spacing. It is found that embedded pile cap condition produced higher resonant frequency and lower resonant amplitude than with no contact condition of pile cap. Both first and second resonant frequencies of pile increase for higher *L/d* ratio. However, both the peak amplitudes decrease for increasing *L/d* ratio. The effect of static loads on the resonant frequency and amplitude of piles were studied and it is observed that the both resonant frequency and amplitude decreased as the static load increased for all the cases.

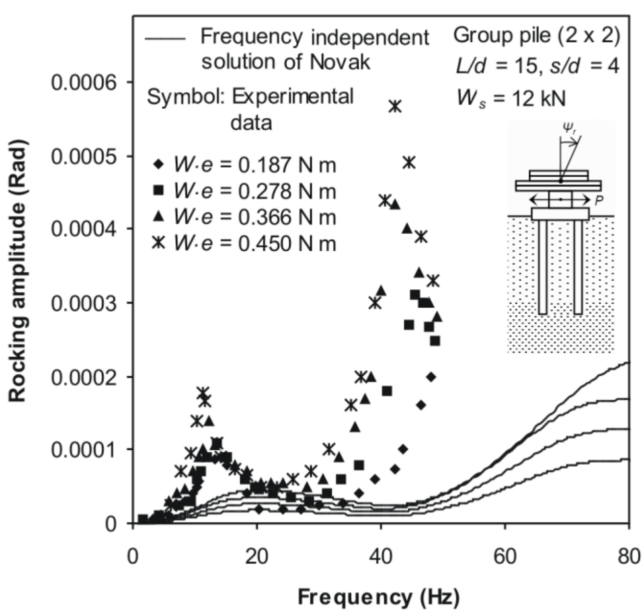
Theory versus Experiment:

Stiffness and damping of single pile were calculated using the Novak's plain strain approach and the static interaction factors used to account for pile group effect. For the piles, Young's modulus (E_p) was taken as 25 x 10^6 kN/m^2 in this analysis. The shear modulus of soil (G_s) was determined from Figure for parabolic soil profile. Based on the values of E_p/G_s ratio and pile length to diameter ratio, the vertical stiffness parameter (f_{w1}), vertical damping parameter (f_{w2}), horizontal stiffness parameter (f_{x1}), horizontal damping parameter (fx_2), rocking stiffness parameter (f_{q1}), rocking damping parameter (f_{q2}), coupled stiffness parameter (f_{xq1}) and couple damping parameter (f_{xq2}) were determined for floating pile and parabolic soil profile from Novak (1974) for L/d=10 and from Novak and El-Sharnouby (1983) for $L/d \geq 15$. The theoretical response curves were obtained by considering static interaction factor between the piles for calculating the stiffness and damping parameters of pile groups. Static interaction factors were calculated at different pile length and pile spacing for Poisson's ratio of 0.35 from Novak and El-Sharnouby (1986). Typical comparison between the experimental and theoretical response curves are shown in Figs. 3 and 4. It can be seen from the figures that the resonant frequency decreases as the exciting intensity increases for experiment. However the resonant frequencies remain constant as the exciting intensity increases for theoretical analysis. In most of the cases, the values of the first and second resonant amplitudes are more in case of experimental value than the analytical results. The first resonant frequency by analysis is very close to the experimental value.

The typical comparison between the experimental results and theoretical results for different conditions of pile like for different spacing ratio (s/d), different embedded conditions of pile caps and for different length (L/d) ratios have been clearly given in the Tables 1, 2 and 3 respectively. It can be seen from Table 1 that as the pile spacing increases the both first and second resonant frequency increases while the both amplitudes decreases in experimental results and linear analysis. It can be seen from Table 2 that for embedded pile cap (Case 1), the values of both resonant frequencies are more and resonant amplitudes are less as compared to no contact condition of pile cap (Case 2). It can be seen from Table 3 that as the L/d increases the resonant frequency increases and the resonant amplitude decreases for most of the cases for both experiment and linear analysis.

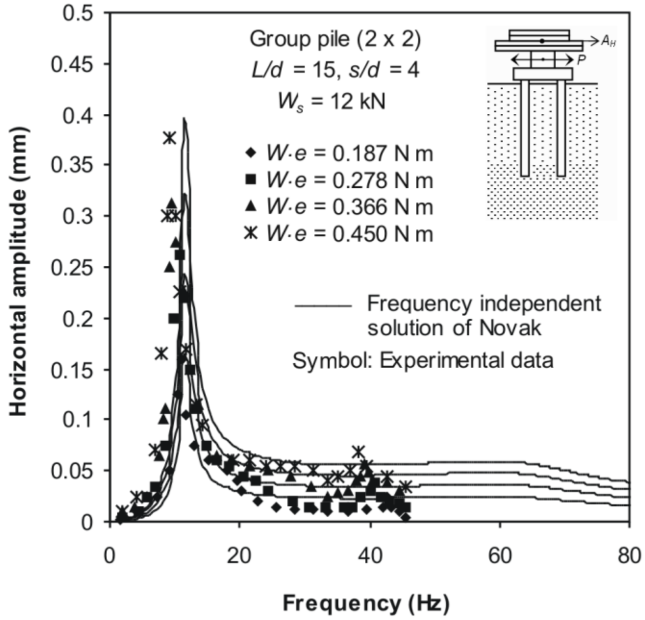


(a)

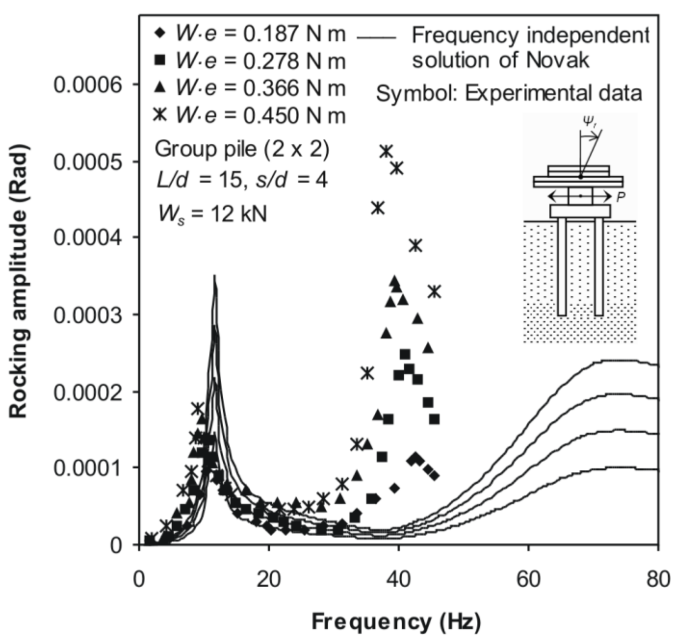


(b)

Fig. 3. Comparison of Experimental Results with that Obtained by Frequency Independent Solution of Novak for Coupled Vibration of Group Pile (L/d = 15, s/d = 4, W_s = 12 kN, Case 1): (a) Horizontal Component, and (b) Rocking Component



(a)



(b)

Fig. 4. Comparison of Experimental Results with that Obtained by Frequency Independent Solution of Novak for Coupled Vibration of Group Pile (L/d = 15, s/d = 4, W_s = 12 kN, Case 2): (a) Horizontal Component, and (b) Rocking Component

Table 1. Comparison of Experimental and Theoretical Results of Coupled Vibration for Single (L/d = 15) and Group Piles (L/d = 15, s/d = 2, 3, 4)

Static load (W_s) = 10 kN, Case 1 - Pile cap embedded in soil (h = 0.175 m)												
Eccentric moment (N m)	**Single pile (L/d = 15)**						**Group pile (2 × 2, L/d = 15, s/d = 2)**					
	f_{n1} (Hz)	$A_{H1\text{-res}}$ (mm)	$\psi_{r1\text{-res}}$ (Rad)	f_{n2} (Hz)	$A_{H2\text{-res}}$ (mm)	$\psi_{r2\text{-res}}$ (Rad)	f_{n1} (Hz)	$A_{H1\text{-res}}$ (mm)	$\psi_{r1\text{-res}}$ (Rad)	f_{n2} (Hz)	$A_{H2\text{-res}}$ (mm)	$\psi_{r2\text{-res}}$ (Rad)
Experimental results												
0.187	7.60	0.125	0.000189	31.23	0.047	0.000209	10.85	0.128	0.000135	44.73	0.0355	0.000181
0.278	6.50	0.168	0.000241	29.03	0.071	0.000353	10.11	0.172	0.000163	42.46	0.0472	0.000303
0.366	5.78	0.208	0.000328	26.68	0.096	0.000511	9.76	0.243	0.000226	40.35	0.0645	0.000414
0.450	4.83	0.238	0.000371	24.88	0.120	0.000642	9.08	0.308	0.000256	38.46	0.0760	0.000606
Linear analysis (Frequency Independent Solution of Novak)												
0.187	10.09	0.0101	0.000018	38.61	0.0215	0.000101	11.52	0.0126	0.000016	64.16	0.0216	0.000086
0.278		0.0151	0.000027		0.0320	0.000150		0.0188	0.000023		0.0321	0.000128
0.366		0.0198	0.000036		0.0421	0.000197		0.0206	0.000031		0.0423	0.000169
0.450		0.0244	0.000044		0.0518	0.000243		0.0304	0.000038		0.0520	0.000208
	Group pile (2 × 2, L/d = 15, s/d = 3)						**Group pile (2 × 2, L/d = 15, s/d = 4)**					
Experimental results												
0.187	12.66	0.110	0.000107	-	-	-	15.13	0.096	0.000095	-	-	-
0.278	11.66	0.165	0.000133	46.58	0.040	0.000269	13.93	0.162	0.000116	-	-	-
0.366	10.73	0.238	0.000167	42.61	0.058	0.000414	12.78	0.218	0.000133	44.68	0.054	0.000312
0.450	9.98	0.275	0.000185	38.85	0.066	0.000611	11.45	0.265	0.000147	41.85	0.067	0.000477
Linear analysis (Frequency Independent Solution of Novak)												
0.187	14.61	0.0158	0.000018	70.15	0.0215	0.000083	17.70	0.0188	0.000018	76.51	0.0212	0.000080
0.278		0.0235	0.000026		0.0320	0.000123		0.0280	0.000027		0.0315	0.000119
0.366		0.0309	0.000035		0.0421	0.000162		0.0368	0.000036		0.0415	0.000156
0.450		0.0380	0.000043		0.0517	0.000199		0.0453	0.000045		0.0510	0.000192

f_{n1}, f_{n2} = first and second resonant frequencies, $A_{H1\text{-res}}$, $A_{H2\text{-res}}$ = first and second resonant amplitudes for horizontal motion,
$\psi_{r1\text{-res}}$, $\psi_{r2\text{-res}}$ = first and second resonant amplitudes for rocking motion

Table 2. Comparison of Experimental and Theoretical Results of Coupled Vibration for Piles of Different Embedded Pile Cap Conditions

Eccentric moment (N m)	**Case 1 - Pile cap embedded in soil (*h* = 0.175 m)**						**Case 2 – No contact of pile cap with soil (*h* = 0)**					
	f_{n1} (Hz)	$A_{H1\text{-res}}$ (mm)	$\psi_{r1\text{-res}}$ (Rad)	f_{n2} (Hz)	$A_{H2\text{-res}}$ (mm)	$\psi_{r2\text{-res}}$ (Rad)	f_{n1} (Hz)	$A_{H1\text{-res}}$ (mm)	$\psi_{r1\text{-res}}$ (Rad)	f_{n2} (Hz)	$A_{H2\text{-res}}$ (mm)	$\psi_{r2\text{-res}}$ (Rad)
Single pile (L/d = 15), Static load (W_s) = 12 kN												
Experimental results												
0.187	6.33	0.131	0.000161	28.30	0.044	0.000193	4.66	0.303	0.000402	23.61	0.049	0.000366
0.278	5.55	0.168	0.000202	26.55	0.078	0.000366	4.06	0.382	0.000505	23.11	0.064	0.000631
0.366	4.68	0.211	0.000301	25.38	0.112	0.000512	2.88	0.575	0.000598	22.46	0.109	0.000876
0.450	4.13	0.244	0.000333	22.41	0.131	0.000721	2.25	0.681	0.000673	21.20	0.137	0.001102
Linear analysis (Frequency Independent Solution of Novak)												
0.187	8.66	0.0086	0.000014	36.19	0.0213	0.000102	3.36	0.8229	0.00120	29.89	0.0322	0.000146
0.278		0.0128	0.000022		0.0317	0.000152		1.223	0.00180		0.0479	0.000217
0.366		0.0168	0.000029		0.0417	0.000201		1.610	0.00240		0.0631	0.000286
0.450		0.0207	0.000035		0.0513	0.000247		1.980	0.00300		0.0776	0.000351
Group pile (2 × 2, L/d = 15, s/d = 4), Static load (W_s) = 12 kN												
Experimental results												
0.187	14.16	0.103	0.000091	-	-	-	11.03	0.160	0.000106	42.58	0.023	0.000115
0.278	13.46	0.134	0.000109	45.51	0.047	0.000311	10.66	0.262	0.000136	40.83	0.038	0.000247
0.366	12.13	0.188	0.000138	42.33	0.058	0.000434	9.63	0.313	0.000165	39.36	0.056	0.000343
0.450	11.60	0.216	0.000166	40.71	0.061	0.000566	9.13	0.370	0.000176	38.21	0.068	0.000512
Linear analysis (Frequency Independent Solution of Novak)												
0.187	15.34	0.0163	0.000015	70.28	0.0183	0.000077	11.57	0.1652	0.000146	67.54	0.0222	0.000092
0.278		0.0242	0.000023		0.0272	0.000115		0.2455	0.000218		0.0331	0.000138
0.366		0.0319	0.000031		0.0358	0.000152		0.3233	0.000287		0.0435	0.000181
0.450		0.0392	0.000038		0.0440	0.000187		0.3975	0.000352		0.0535	0.000223

f_{n1}, f_{n2} = first and second resonant frequencies, $A_{H1\text{-res}}$, $A_{H2\text{-res}}$ = first and second resonant amplitudes for horizontal motion,
$\psi_{r1\text{-res}}$, $\psi_{r2\text{-res}}$ = first and second resonant amplitudes for rocking motion

Table 3. Comparison of Experimental and Theoretical Results of Coupled Vibration for Group Piles (s/d = 4, W_s = 12 kN, Case 2) of different L/d ratio

Eccentric moment (N m)	**Static load (W_s) = 12 kN, Case 2 – No contact of pile cap with soil (h = 0)**											
	f_{n1} (Hz)	$A_{H1\text{-res}}$ (mm)	$\psi_{r1\text{-res}}$ (Rad)	f_{n2} (Hz)	$A_{H2\text{-res}}$ (mm)	$\psi_{r2\text{-res}}$ (Rad)	f_{n1} (Hz)	$A_{H1\text{-res}}$ (mm)	$\psi_{r1\text{-res}}$ (Rad)	f_{n2} (Hz)	$A_{H2\text{-res}}$ (mm)	$\psi_{r2\text{-res}}$ (Rad)
Group pile (2 × 2, L/d = 10, s/d = 4)												
	Experimental results						**Frequency Independent Solution of Novak**					
0.187	9.31	0.192	0.000165	39.25	0.056	0.000127	5.40	0.3099	0.000408	74.91	0.0234	0.000082
0.278	9.06	0.272	0.000216	37.40	0.059	0.000233		0.4608	0.000606		0.0348	0.000122
0.366	8.56	0.355	0.000230	36.20	0.062	0.000369		0.6066	0.000798		0.0459	0.000161
0.450	8.28	0.424	0.000275	35.38	0.069	0.000487		0.7459	0.000982		0.0564	0.000198
Group pile (2 × 2, L/d = 15, s/d = 4)												
	Experimental results						**Frequency Independent Solution of Novak**					
0.187	11.03	0.160	0.000106	42.58	0.023	0.000115	11.57	0.1652	0.000146	67.54	0.0222	0.000092
0.278	10.66	0.262	0.000136	40.83	0.038	0.000247		0.2455	0.000218		0.0331	0.000138
0.366	9.63	0.313	0.000165	39.36	0.056	0.000343		0.3233	0.000287		0.0435	0.000181
0.450	9.13	0.370	0.000176	38.21	0.068	0.000512		0.3975	0.000352		0.0535	0.000223
Group pile (2 × 2, L/d = 20, s/d = 4)												
	Experimental results						**Frequency Independent Solution of Novak**					
0.187	13.66	0.235	0.000075	44.93	0.032	0.000143	13.09	0.1618	0.000132	72.22	0.0210	0.000096
0.278	11.93	0.289	0.000098	42.66	0.042	0.000268		0.2405	0.000197		0.0329	0.000143
0.366	10.93	0.321	0.000125	40.21	0.059	0.000367		0.3166	0.000259		0.0433	0.000189
0.450	10.16	0.365	0.000144	37.80	0.062	0.000485		0.3893	0.000319		0.0532	0.000233

f_{n1}, f_{n2} = first and second resonant frequencies, $A_{H1\text{-res}}$, $A_{H2\text{-res}}$ = first and second resonant amplitudes for horizontal motion,
$\psi_{r1\text{-res}}$, $\psi_{r2\text{-res}}$ = first and second resonant amplitudes for rocking motion

Conclusions

The main emphasis in this present work is to compare a huge number of dynamic test results of pile (Manna, 2009) under coupled vibration with plane strain model of Novak (1974) with static interaction factor approach and check the accuracy of the theoretical model. The influence of pile-soil-pile interaction on the coupled dynamic behavior of pile groups has investigated using static interaction factor approach. It is found from the analytical investigation that many parameters like exciting intensities, static load, embedment of pile cap, different *L/d* and *s/d* ratio have an influence on the dynamic response of pile foundation under coupled vibration.

A comprehensive study involving both model dynamic testing of pile foundation and theoretical analysis have been described in the paper. Coupled vibration tests with model reinforced concrete single pile and pile groups embedded in layered soil have conducted in the field. A large number of tests with different exciting moments and different embedded conditions of pile cap were considered. The measured data of single pile and group pile were compares with the theoretical value with one approach namely, the Novak's frequency independent approach. The pile-soil-pile interaction on the coupled dynamic behavior of pile groups was investigated using static interaction factor approach. Some important conclusions that can be made from the study performed are as follows:

1. Many parameters like exciting intensities, dynamic load, embedded of pile cap and *L/d* and *s/d* ratios have an influence on the dynamic response of pile foundation under coupled vibration.
2. The resonant frequency decreases as the exciting intensity increases for experiment but the resonant frequencies remain constant as the exciting intensity increases for theoretical analysis.
3. The values of the first and second resonant amplitudes are more in case of experimental value than the analytical results.
4. The first resonant frequency by analysis is very close to the experimental value.

5. The both first and second resonant frequency increases while the both amplitudes decreases as the pile spacing increases in experimental results and linear analysis.
6. For embedded pile cap (Case 1), the values of both resonant frequencies are more and resonant amplitudes are less as compared to no contact condition of pile cap (Case 2).
7. The resonant frequency increases and the resonant amplitude decreases as the *L/d* increases for most of the cases for both experiment and linear analysis.

The experimental data presented in this paper could be analyzed to correlate different influencing parameters with dynamic behavior of pile foundation and these data may prove useful for future research purpose as well as for the practicing engineers.

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